

Coupled Circulation, Wave, and Morphology-Change Modeling, Shinnecock Inlet, New York

¹Frank S. Buonaiuto, and ²Adele Militello

Abstract

Analysis of five high-resolution bathymetric data sets collected at Shinnecock Inlet, NY indicates the evolution of ebb shoal morphology between 1994 and 2000 was primarily controlled by migration of the main navigation channel. Increased wave activity during the 1997 El Nino accelerated the rate at which the channel was deflected toward the west. These bathymetric data are applied in this study for assessment of morphology change calculation conducted within the Inlet Modeling System developed by the U.S. Army Corps of Engineers Coastal Inlets Research Program. Circulation, sediment transport, and morphology change were calculated by the two-dimensional finite-difference model M2D, which was coupled with STWave for computation of wave-driven currents. A simulation was conducted for August to November 1997 in which waves from NDBC Station 44025 were input as forcing for STWave. Tidal forcing for M2D was prescribed with water levels extracted from a regional ADCIRC model. Major observed changes in inlet morphology were reproduced by the modeling system. These changes are: scour and westward migration of the navigation channel, accretion along the eastern flank of the ebb shoal, and accretion of the seaward extent of the ebb shoal.

Introduction

Shinnecock Inlet, located on the south shore of Long Island, New York (Fig. 1), opened on September 21, 1938 during the passage of the Great New England Hurricane (Morang 1999). Since its opening, inlet evolution has been influenced by storms, dredging, beach nourishment projects, and construction and rehabilitation of two offset rubble-mound jetties originally built between 1953 and 1954. Morphology of the inlet and ebb shoal is controlled by tide and wave-driven transport, as well as by jetties and bathymetric features such as channels and shoals. Tide on the south shore of Long Island is semidiurnal with a mean range of 0.88 m at the inlet entrance (ocean side). Spring tide range is 1.1 m and the tidal prism is $3.29 \times 10^7 \text{ m}^3$ (Militello and Kraus 2001). Incident waves have average height of approximately 1 m and

1) Coastal Oceanographer. Marine Sciences Research Center, SUNY at Stony Brook, Stony Brook NY 11794-5000. fsbuonaiuto@optonline.net.

2) Physical Oceanographer. Coastal Analysis LLC, 4886 Herron Road, Eureka, CA 95503. CoastalAnalysis@cox.net.

period of 7 sec, originating from the southeast. During large northeaster storms and hurricanes, wave height can exceed 4 m with periods in the range of 12-14 sec.

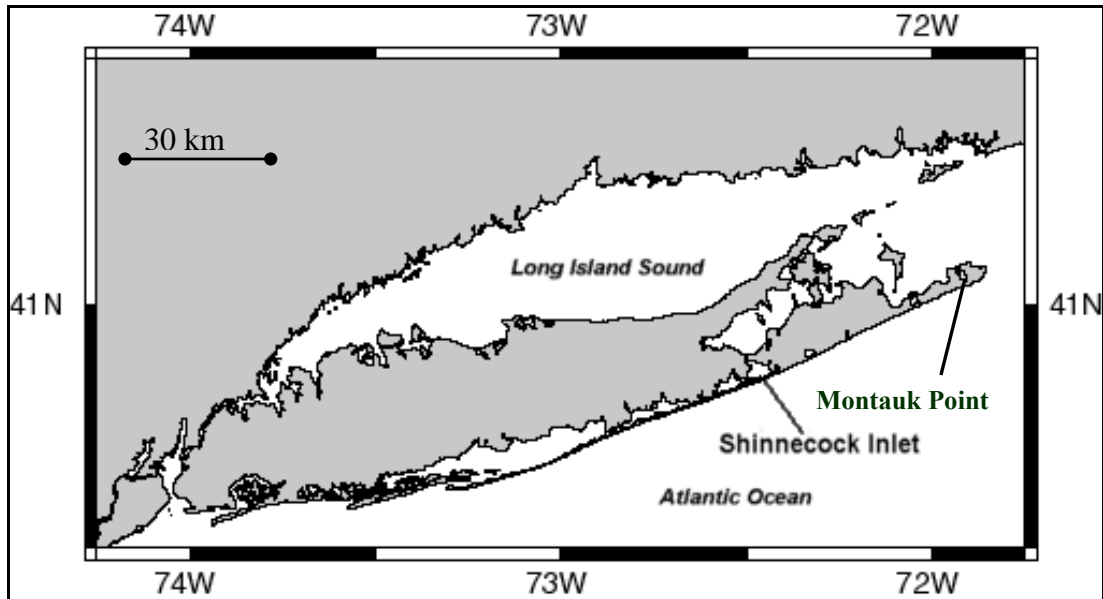


Figure 1. Location map for Shinnecock Inlet, NY.

During the 1997 to 1998 fall and winter season, increased transport and wave activity enhanced the natural westward migration of the main navigation channel (Buonaiuto 2003a). Channel reorientation potentially altered the transport conduits and delivery of sediment to the morphologic features that comprise the ebb shoal complex (Fig. 2). The movement of sediment was further complicated by an increase in annual wave energy from the east associated with larger climatic cycles.

The Inlet Modeling System (IMS) developed by the U.S. Army Corps of Engineers (USACE) Coastal Inlets Research Program (CIRP) was applied to Shinnecock Inlet with the main objective of simulating transport pathways and evolution of morphology arising from the increased supply of littoral sediments that took place from August 1997 to May 1998. The modeling system was used to gain insight into the complex hydrodynamics and transport processes that control the distribution of sediment around the inlet and ebb shoal. Acknowledging that the IMS was a relatively new tool available to coastal engineers and scientists, the numerical calculations were supplemented with more standard coastal engineering analyses of the inlet. The IMS replicated theoretical and observed trends in inlet behavior including deepening and deflection of the channel, increasing volume of the ebb shoal complex, and sediment bypassing across the inlet. Additionally the IMS furthered understanding of the natural rotation of the ebb jet and its interaction with wave-driven longshore currents, processes that could not be discerned from traditional engineering techniques.

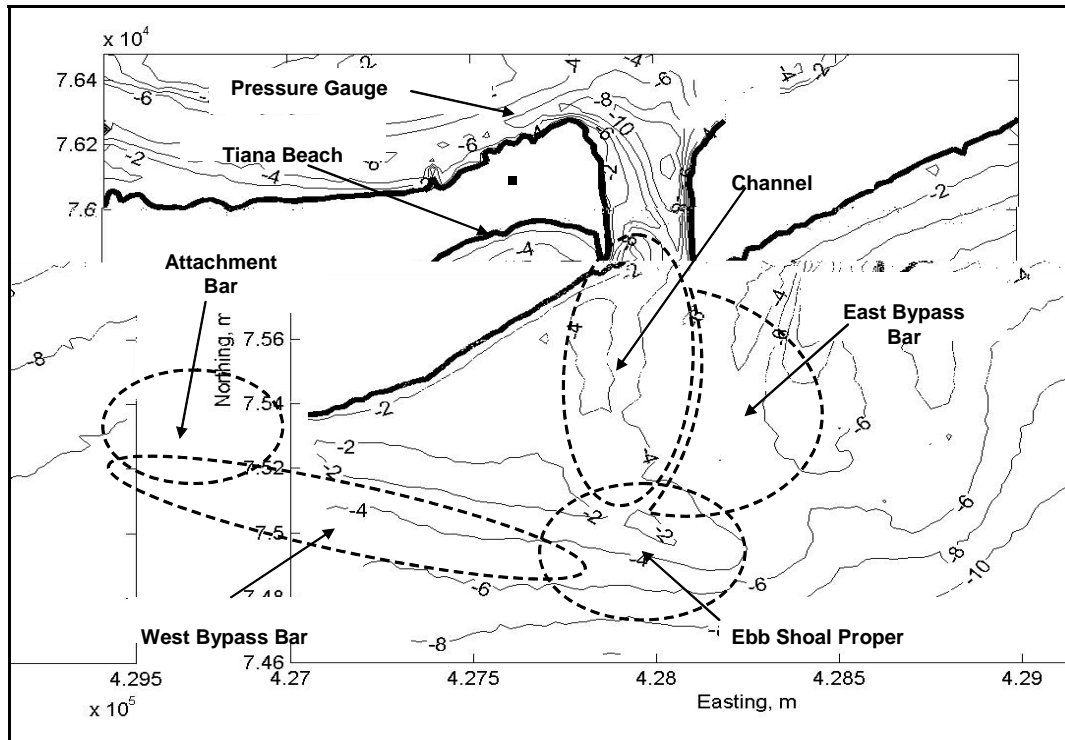


Figure 2. 1997 Shinnecock Inlet ebb shoal complex.

Morphology Change Analysis

Predictive relationships have been applied to Shinnecock Inlet to address the primary processes operating around the inlet and its general stage of development or evolution. Several investigators have identified a correlation between tidal prism of an equilibrium inlet and the cross sectional area of the throat (LeConte 1905; O'Brien 1931, 1969; Jarrett 1976). The empirical equation is,

$$A_c = CP^n \quad (1)$$

where A_c is the channel cross-sectional area, P is the tidal prism, and C and n are empirical coefficients. Values of C and n depend on the number of jetties present at the inlet and the general wave climate. For Shinnecock Inlet the coefficients C and n are 5.77×10^{-5} and 0.95 respectively. Application of the Jarrett (1976) equation to Shinnecock Inlet using the 1998 estimate of tidal prism indicates the minimum cross-sectional area in the throat of the inlet should approach $2,177 \text{ m}^2$ (Buonaiuto 2003b). A previous estimate gave a minimum inlet cross-sectional area of $2,694 \text{ m}^2$ (Militello and Kraus 2001). These empirically-estimated minimum cross-sectional areas are larger than those measured in 1994 ($1,551 \text{ m}^2$) and 1998 ($1,566 \text{ m}^2$) (Morang 1999). Between 1994 and 1998 the cross-sectional area of the channel increased, indicating that the inlet was scouring toward the predicted equilibrium flow area.

The dominant direction of longshore transport along the south shore of Long Island is from east to west (Taney 1961; Panuzio 1968). Seasonal winds from the west and southwest in summer can induce short-term transport reversals along the

eastern half of Long Island. Littoral sediments on eastern Long Island have been assumed to be supplied either from bluff erosion at Montauk Point, or from offshore sources (Taney 1961; Kana 1995; Williams 1976; Schwab et al. 1997). Sediment budget analyses indicate that the inlet removes sediment from the littoral system at a rate of 70,000 to 115,000 m³/year (USACE 1958, 1988; Kana 1995; Morang 1999; Rosati et al. 1999). Empirical relations are available to estimate the large volume of sediment contained in the ebb and flood shoals (Dean and Walton 1975; Walton and Adams 1976; Carr de Betts 1999). Properties of inlets along the Atlantic, Gulf, and Pacific coasts of the United States were examined, and the combined control by the tide and waves were related to the ebb shoal volume as (Walton and Adams 1976),

$$V_s = CP^n \quad (2)$$

where V_s is ebb shoal volume, and C and n are empirical coefficients that depend on wave energy. For Shinnecock Inlet, a moderately exposed inlet, the coefficients C and n are 10.5×10^{-5} and 1.23 respectively. Using the most recent estimate of tidal prism, application of Eq. 2 to the inlet gives an equilibrium ebb shoal volume of approximately 11,200,000 m³. This empirically-estimated volume is larger than the amount of material contained in the ebb shoal in 1996 (5,803,000 m³), 1997 (5,988,000 m³), and 1998 (6,463,000 m³) (Morang 1999). Increase in volume between 1996 and 1998 indicates the ebb shoal complex was trapping sediment prior to the dredging of the channel and deposition basin in 1998. By 1998, the ebb shoal had trapped 60 % of the theoretical equilibrium volume. Using the estimated rates of trapping, the ebb shoal is expected to attain equilibrium in approximately 42 to 70 years. A previous calculation of the theoretical ebb shoal volume determined equilibrium would be reached in approximately 75 years, although dredging of the channel and ebb shoal would prolong the evolution (Kraus 2001). As equilibrium is approached, it is expected that more persistent sediment transport pathways will be established, and the inlet will bypass sediment more effectively to the neighboring beaches.

Inlet morphology responds to variations in gross longshore sediment transport rates, which have been estimated to range from 230,000 m³/year to 305,000 m³/year in the vicinity of Shinnecock Inlet (Williams et al. 1998). Easterly transport predominates during the months of May through August, and during December. West-directed transport dominates the remainder of the year with the largest overall net transport rates (for either direction) occurring between the months of September and November. Inlet sediment bypassing controls the rate, location, and composition (Bruun and Gerritsen 1959, 1960; Liu and Hou 1997) of sand nourished to downdrift beaches. Sediment bypassing across inlets is achieved through the transport modes of 1) wave-induced transport along the periphery of the ebb shoal (terminal lobe), 2) transport through channels by tidal currents, and 3) migration of tidal channels and sand bars (Bruun and Gerritsen 1959, 1960). The dominant mode of sediment bypassing can be determined from the ratio,

$$r = P/M \quad (3)$$

which expresses the balance between the gross longshore sediment transport rate M brought to the inlet annually and the tidal prism. Inlets with high ratios ($r > 150$) bypass sand predominantly through tidal flushing, whereas inlets with low values ($r < 50$) bypass sand predominantly through channel migration and bar complex formation. Inlets with ratios ranging between 50 and 150 generally develop large ebb shoals and bypass sediment across the throat of the inlet (tidal flushing) and along the periphery of the ebb shoal (sand bridge transport). Application of Eq. 3 to Shinnecock Inlet using the most recent estimate of the gross longshore sediment transport rate (Williams et al. 1998) and tidal prism (Militello and Kraus 2001) resulted in an r parameter ranging between 107 and 143, which suggests natural sediment bypassing at Shinnecock Inlet should occur through a combination of wave-induced transport and tidal bypassing.

Principal Component Analysis (PCA) was applied to the bathymetry data to identify spatial patterns of morphology change (Buonaiuto 2003b). Bathymetric data used in the PCA were collected by the USACE's water-penetrating LIDAR system called SHOALS. The analysis indicated the locations of the bypassing bars, ebb shoal, and attachment point, were largely controlled by the position of the navigation channel. From 1994 through 2000, Shinnecock Inlet experienced a period of growth accreting almost 2,000,000 m³ of sediment along the ebb shoal proper, bypass bar and attachment point (Fig. 3). Between 1994 and 1997 the inlet accreted sediment along the periphery of the ebb shoal, which included the eastern, up-drift flank of the main channel (eastern ebb shoal lobe), the ebb shoal saddle, the western, down-drift portion of the ebb shoal, the bypass bar and the attachment point (Fig. 4). Sediment was also deposited as a linear shoal extending from the tip of the western jetty along the west side of the channel. During this period the main channel appeared to scour between 1 and 2 m.

From 1997 to 1998, the Shinnecock Inlet system showed a net accretion of 530,000 m³. Sediment was deposited along the periphery of the western lobe of the ebb shoal and along the bypass bar. As the channel was naturally redirected toward the west, the shoal that extended from the tip of the western jetty began to erode. Additionally the landward face of the bypass bar eroded as the deflected ebb jet drove sediment reserved in the bypass bar further offshore (Fig. 5). Dredging of the channel and deposition basin in 1998 re-oriented the entrance toward the south, promoting growth and seaward advancement of the ebb shoal proper.

As the channel naturally migrated, the westward movement of sediment deposited on the eastern flank was accelerated by increased wave driven-currents from the east. Analysis of ten years of directional wave data collected from National Data Buoy Center (NDBC) station 44025 located 33 nautical miles off the coast of Long Island (Buonaiuto 2003a) indicated an increase in wave activity from the east quadrant between the 1997 and 1998 surveys associated with the ENSO (El Nino southern Oscillation) cycle (Fig. 6).

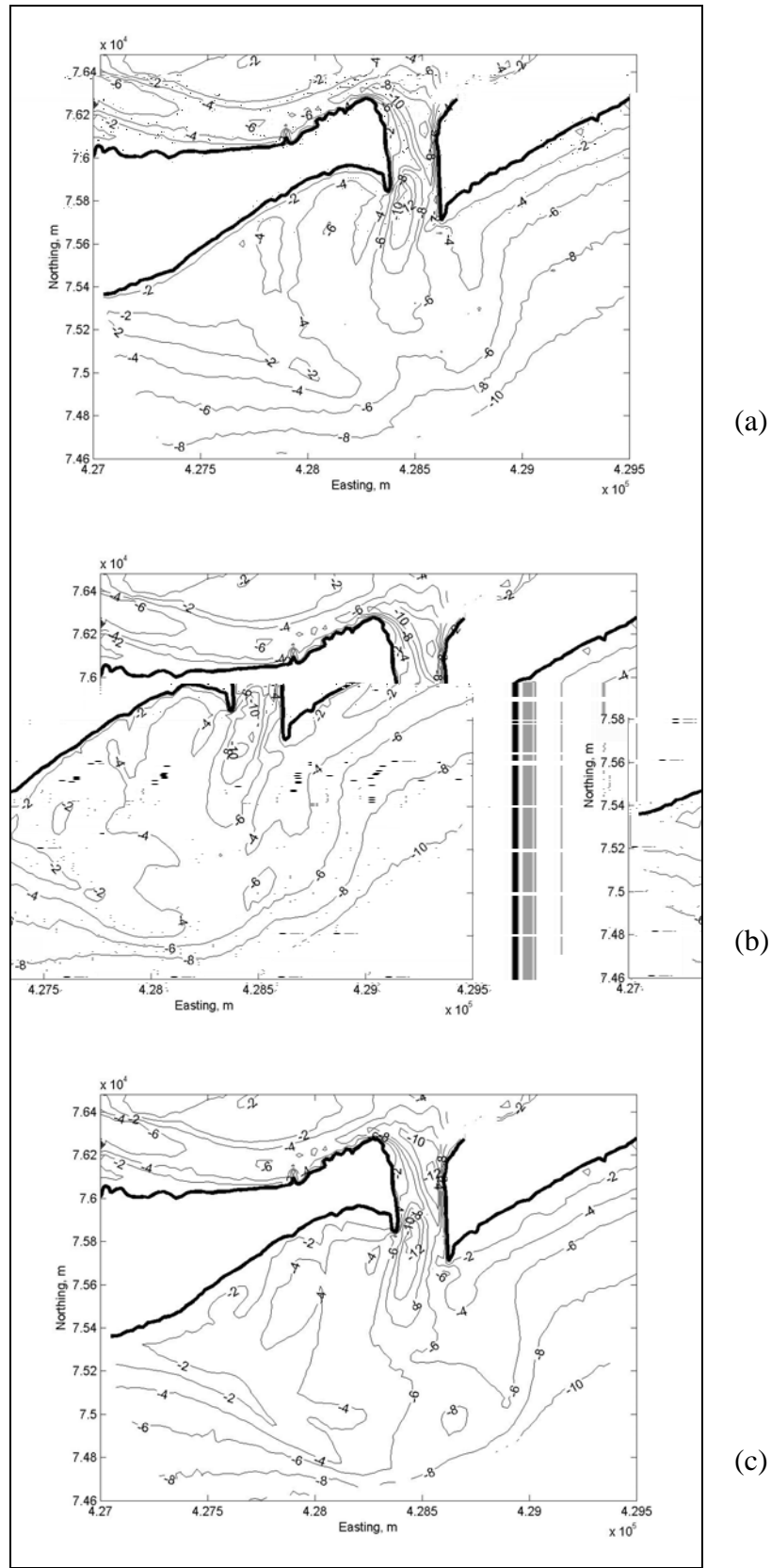


Figure 3. Shinnecock Inlet morphology captured during the 1997 (a), 1998 (b) and 2000 (c) SHOALS surveys.

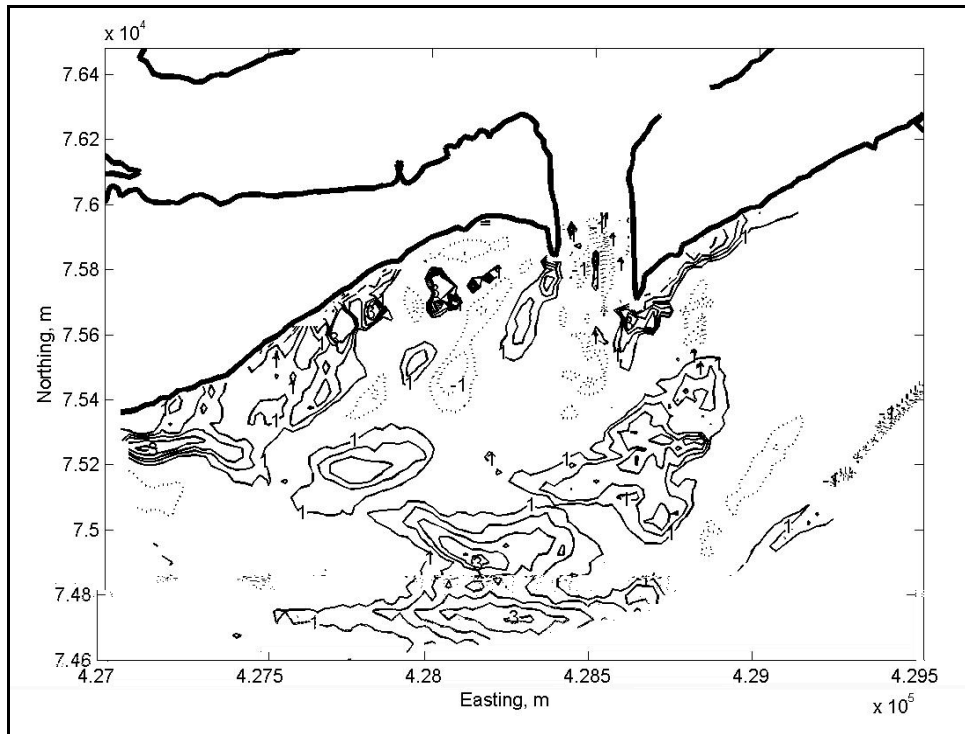


Figure 4. Depth changes between the 1994 and 1997 SHOALS surveys. Contour labels are in meters. Solid contours indicate areas of accretion and dotted contours mark zones of erosion.

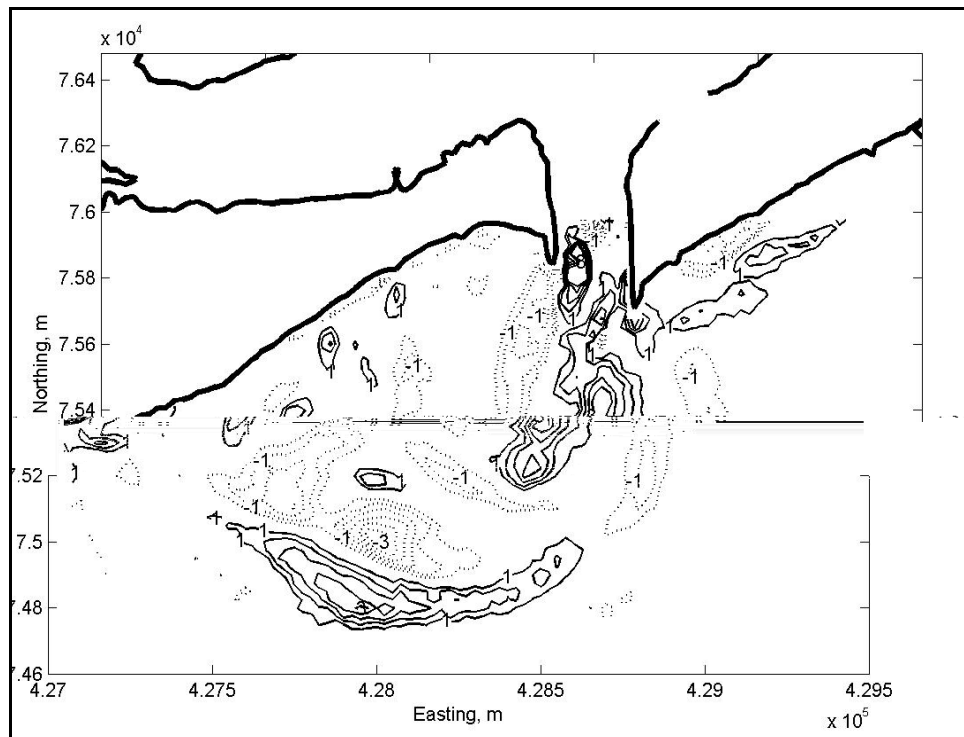


Figure 5. Depth changes between the 1997 and 1998 SHOALS surveys. Contour labels are in meters. See Fig. 4 for description.

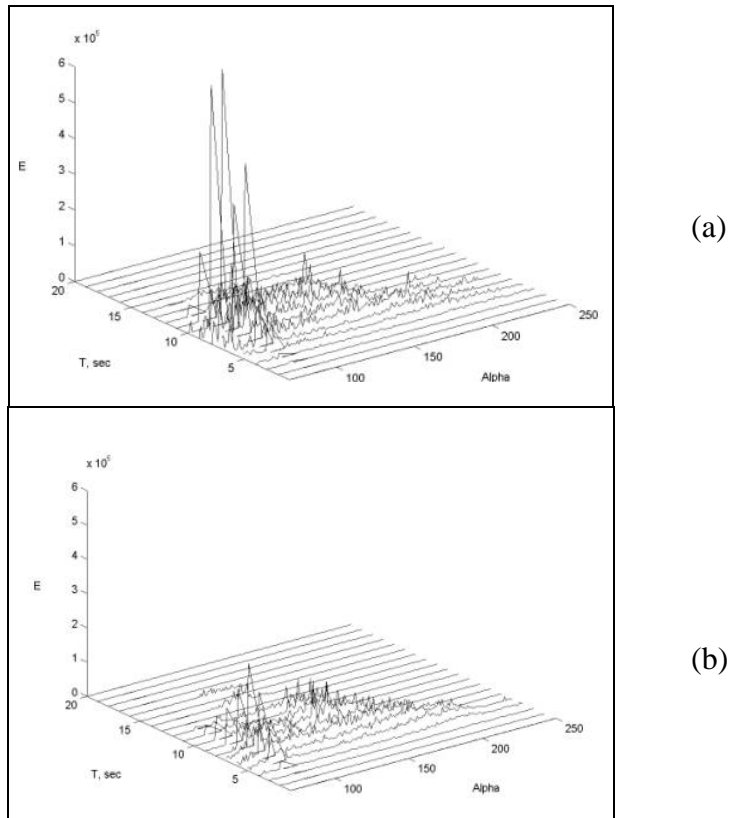


Figure 6. Incident wave spectrum for 1997 (a) and 1998 (b) JMA calendar years.

Prior to the 2000 survey the channel and deposition basin were dredged which effectively removed 336,404 m³ of material (Table 1). During this period an additional 10,277 m³ of sediment naturally eroded from the ebb shoal. Although there was deflation of the bypass bar and an overall net loss of material from the system, the periphery of the ebb shoal prograded seaward as a result of the re-orientation and deepening of the channel (Fig. 7).

Table 1: Recent Event and Activity Chronology

| | |
|---------------------|---|
| 6/21/94 | SHOALS LIDAR bathymetric survey |
| 5/23/96 | SHOALS LIDAR bathymetric survey |
| 2/97 – 3/97 | Shinnecock Flood Shoal Dredging 250,000 yd ³ removed from eastern flood shoal channel |
| 8/13/97 | SHOALS LIDAR bathymetric survey |
| 5/28/98 | SHOALS LIDAR bathymetric survey |
| 6/27/98 – 7/11/98 | Shinnecock Inlet Dredging 35,000 yd ³ removed from entrance channel and deposition basin |
| 10/13/98 – 10/25/98 | Shinnecock Inlet Dredging 405,000 yd ³ removed from entrance channel and deposition basin |
| 7/3/00 | SHOALS LIDAR bathymetric survey |

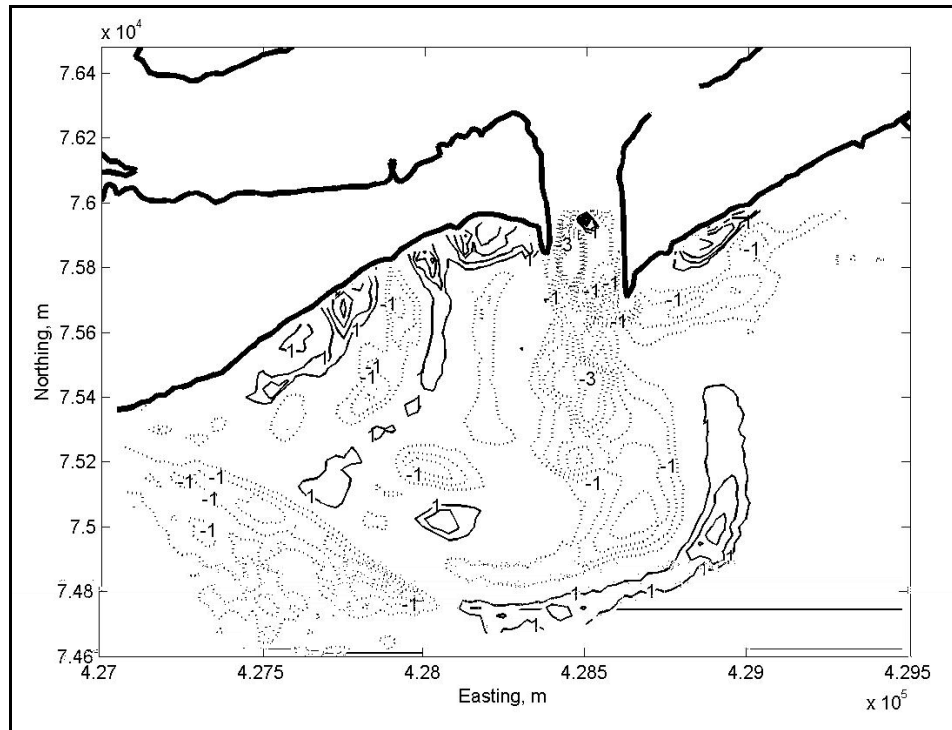


Figure 7. Depth changes between the 1998 and 2000 SHOALS surveys. Contour labels are in meters. See Fig. 4 for description.

Modeling Approach

The IMS was applied to simulate the natural migration of the inlet channel between the 1997 and 1998 surveys. The IMS consists of a suite of models implemented within the Surfacewater Modeling System (Zundel 2000) and designed to compute tidal hydrodynamics, wave transformation, sediment transport and morphology change. Models can be coupled for specific application requirements. For this investigation, water-surface elevations and current velocities were computed by M2D, a localized two-dimensional, depth-integrated, hydrodynamic model developed for shallow-water regions (Militello et al. 2004). M2D solves finite-difference approximations of the nonlinear equations of mass and momentum conservation on a variably-spaced rectilinear grid. Advection, mixing, and quadratic friction are represented in the model. Sediment transport and morphology change can be computed by M2D as a user-specified option.

Wave transformation was computed by STWave (Smith et al. 2000), a steady-state finite-difference spectral wave model based on the wave action balance equation. The model calculates depth- and current-induced wave refraction and shoaling, depth- and steepness-induced wave breaking, wave growth due to local wind stress, wave-wave interactions, and white capping. Calculations are conducted on a constant-spaced rectilinear grid.

M2D and STWave were coupled for calculation of wave-driven currents. Radiation stress gradients calculated by STWave were mapped onto the M2D grid to supply wave forcing. Total water depths calculated by M2D were mapped to the

STWave grid so that the temporal modulation of wave properties with changes in water level was represented. Coupling between M2D and STWave was set at 3-hr intervals.

Sediment transport and morphology change were calculated within M2D. Combined wave- and tide-driven velocities were entered into computations of local shear stress and sediment transport rates were calculated by the Watanabe (1987) total load formulation,

$$q_t = A \left[\frac{(\tau_b - \tau_{cr})V}{\rho_w g} \right] \quad (4)$$

where q_t is the total load (both suspended and bed), τ_b is the shear stress at the bed, τ_{cr} is the shear stress at incipient sediment motion, V is the depth averaged current velocity as provided by the coupled model, ρ_w is the density of water, g is the gravitational acceleration constant (9.81 m/s^2), and A is an adjustable coefficient (0.5 – 2 for regular to irregular waves). For this investigation the sediment was considered to be homogeneous medium sand. Transport rates for each M2D cell were computed every 100 seconds. Through mass conservation, the bathymetry was updated at 6-hr intervals giving morphology change of the inlet, shoals, and nearshore region. At each bathymetric update, new depths were provided to the hydrodynamic component of the model for calculation of velocity and water level response to changes in morphology.

Grid Development

Bathymetric data for the M2D and STWave grids were obtained from several sources including NOAA, GEODAS, Marine Science Research Center State University of New York at Stony Brook, and USACE. Bathymetry covering the region surrounding Shinnecock Inlet (ebb shoal, throat, and flood shoal) was obtained from the August 13, 1997 and the May 28, 1998 SHOALS surveys. Model grids cover all of Shinnecock Bay and extend up and downdrift of the inlet to regions unaffected by the ebb-tidal shoal (Fig. 8). Seaward boundaries extend offshore to 30 m water depth, beyond the zone where wave shoaling takes place and beyond the closure depth and farthest seaward extent of the ebb jet.

The STWave grid was specified to have 20-m spacing over its domain. This spacing provides several cells per wavelength and adequately resolves the radiation-stress gradients within the shoaling, breaking and surf zones, leading to more accurate calculation of water levels and currents there. The M2D grid was developed such that the cell spacing was 100 m in the deeper water offshore, and transitions to 10 m near the coastline, inside the wave shoal zone, around the flood and ebb shoals, and in the inlet throat (Fig. 9). Wave transformation in these regions takes place over relatively short distances and greater resolution was specified in areas so that details of the circulation and sediment transport would be reproduced. The two grids (STWave and M2D) covered identical geographical regions (Fig. 8).

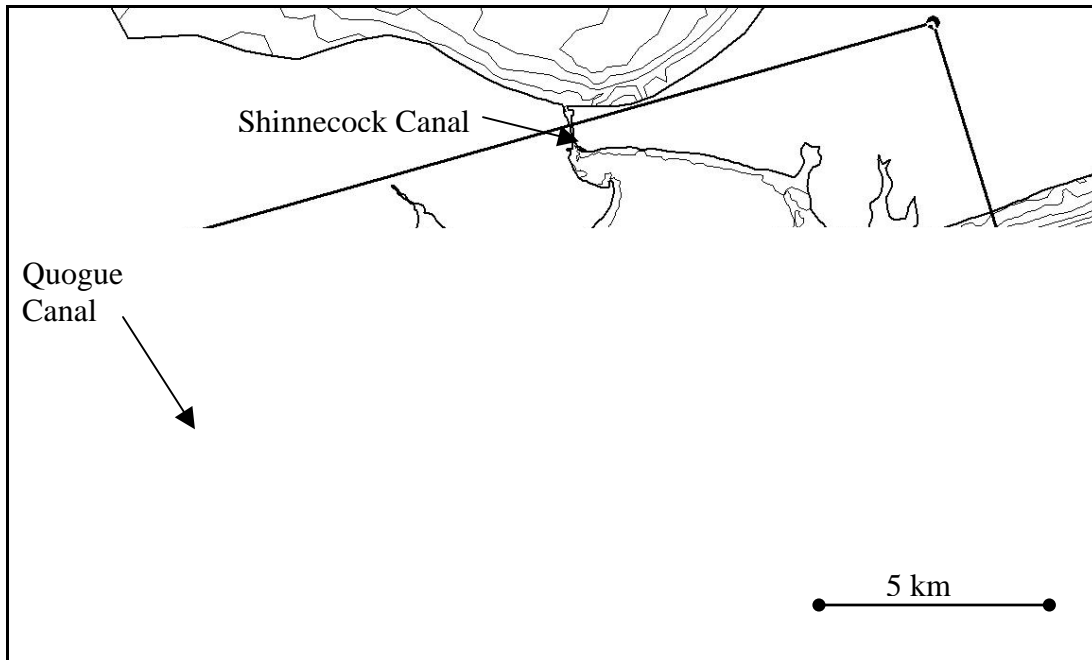


Figure 8. IMS Shinnecock Inlet domain.

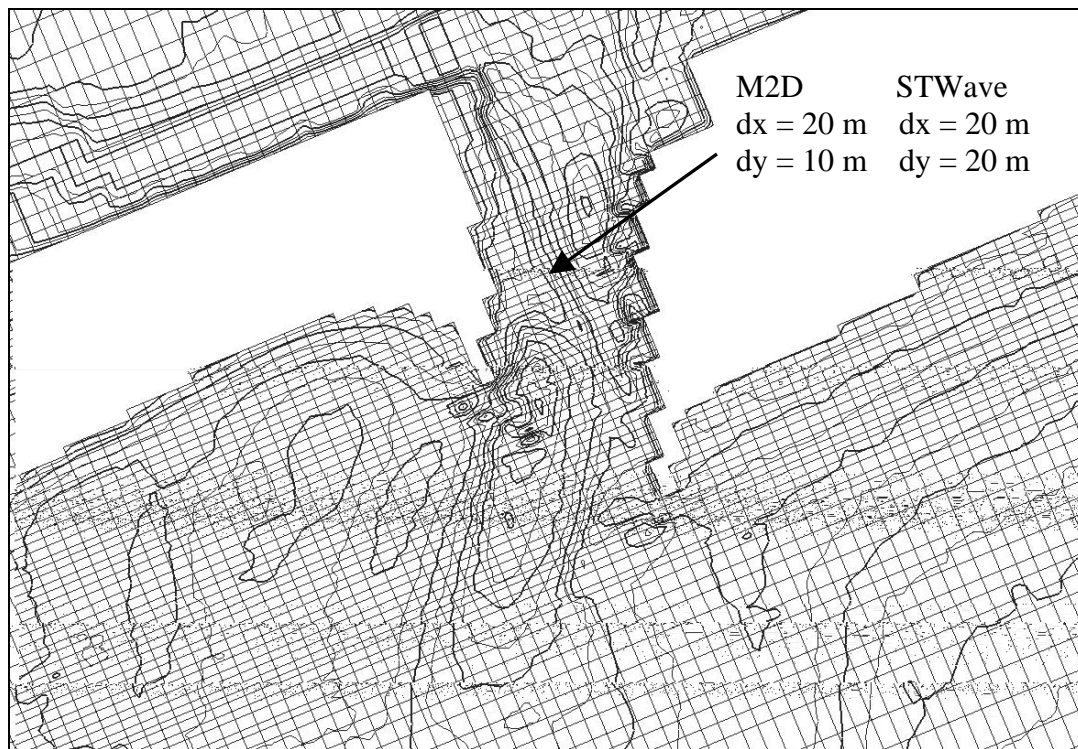


Figure 9. IMS-M2D grid of Shinnecock Inlet. Finer resolution was implemented throughout the surfzone and throat of the inlet.

Model Verification

In order to verify the M2D model, calculated water levels were compared to measurements collected during 1998 as part of a field monitoring system sponsored by the USACE New York District, the CIRP, and the New York State Department of Environmental Conservation. For the verification, M2D was forced with water-surface elevation values along the seaward boundary and at the Shinnecock and Quogue canals. Water levels were extracted from the regional ADCIRC model of Long Island (Militello and Kraus 2003) from November 4, 1998 through November 16, 1998. Wave forcing was not included in the verification, and calculation of sediment transport rates and morphology change was not invoked. Field data used for comparison were collected by a pressure gauge mounted along the bay side of Shinnecock Inlet near the western barrier. Results indicate the tidal elevation was well predicted (Fig. 10), and the calculated tidal range was within 12 percent of the observations. This error was comparable to that of the ADCIRC calculations for the same location (Militello and Kraus 2001a), indicating that the primary source of error was introduced by the boundary conditions obtained from the regional model. A meteorological event occurred during November 10 through November 14. The measured water level shows response to this atmospheric forcing. However, calculations for model verification were forced with tide alone so they do not contain deviations owing to wind events. Presently wind forcing can only be implemented as a constant stress and would not be applicable in a time varying simulation.

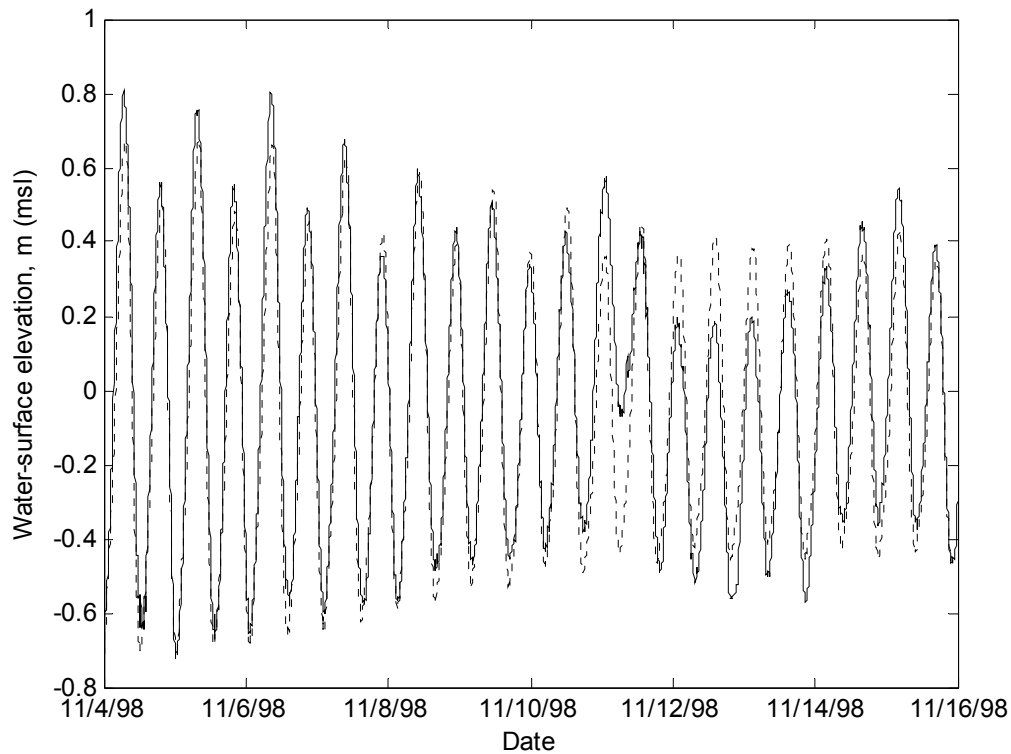


Figure 10. M2D model verification bay side of Shinnecock Inlet. Observed data indicated by solid black line, calculated water level shown as dotted line.

Model Forcing

Calculation of morphology change was conducted during a time in which controlling factors ranged from primarily tidal to storm dominated. The simulation time interval was specified to coincide with the natural deflection and migration of the main navigation channel through the ebb shoal. Data collected during two SHOALS surveys conducted on August 13, 1997 and May 28, 1998 provide bathymetric change information from which the calculations can be verified. M2D was forced by both water-surface elevation along the seaward boundary and wave-driven radiation stress gradients within the interior of the domain. Boundary conditions for the local model (M2D) were extracted from the regional ADCIRC model of Long Island and mapped to the seaward boundary, Quogue Canal boundary, and Shinnecock Canal boundary. This method of boundary specification preserves temporal and spatial variation of tidal properties at the boundaries. Thus, interior response to spatial amplitude and phase variation is included in the calculations. In the nearshore region, the coastal tidal current is represented which enhances the natural westward migration of the ebb jet.

Incident wave field characteristics (height, period, and direction) were obtained from NDBC Station 44025 and used to construct spectral energy input files for STWave. The spectrums were applied along the offshore boundary and propagated to the shoreline by STWave. During the simulation wave conditions were updated at 3-hr intervals and radiations stress gradients were calculated across the STWave model domain.

Simulation Results

Results presented in this section represent a 15-week-long time interval that started on August 13, 1997 and ended on November 30 1997. To reproduce morphology change the model simulation was condensed to a 4-week-long sequence during which incident wave fields with wave heights greater than 1 m and periods larger than 7 sec were modeled. These wave fields were chosen to represent events that forced peak transport of littoral material. By including August and September, when wave forcing was relatively weak, tidal control on morphology change could be evaluated. Sediment transport rates were computed each hour and the inlet morphology was updated four times each day based on 6-hr averages of the sediment transport rates. Calculated depth was output every 24 hr, and bathymetric change (Figs. 11-13) was plotted at the end of each month.

During the months of August and September, Shinnecock Inlet experienced relatively low wave energy. Therefore, during this time morphology change responded to tides and relatively weak waves. Wave heights rarely exceeded 1.5 m and periods ranged between 5 and 9 sec. The longest-period swell (11 to 14 sec) to reach the inlet between the 1997 and 1998 surveys occurred in mid-September. Although the swells approached from the south and lasted four days, wave heights did not exceed 1.75 m. The absence of long-period swells in the wave record during the simulation owes to a reduction in hurricane activity during El Nino years

(October 1, 1997 through September 30, 1998) (Bove et al., 1998). Morphology change calculations for the end of September indicate that active transport regions were primarily located in the throat of the inlet, and in the direct path of the ebb jet (Fig. 11). The channel extending from the jetty tips and across the ebb shoal eroded along its western flank, reproducing the measured trend of westward channel migration. Deposition took place updrift (east) of the channel. Small bar complexes offshore of Tiana Beach were translated along the western barrier within the wave-shadowed region of the ebb shoal.

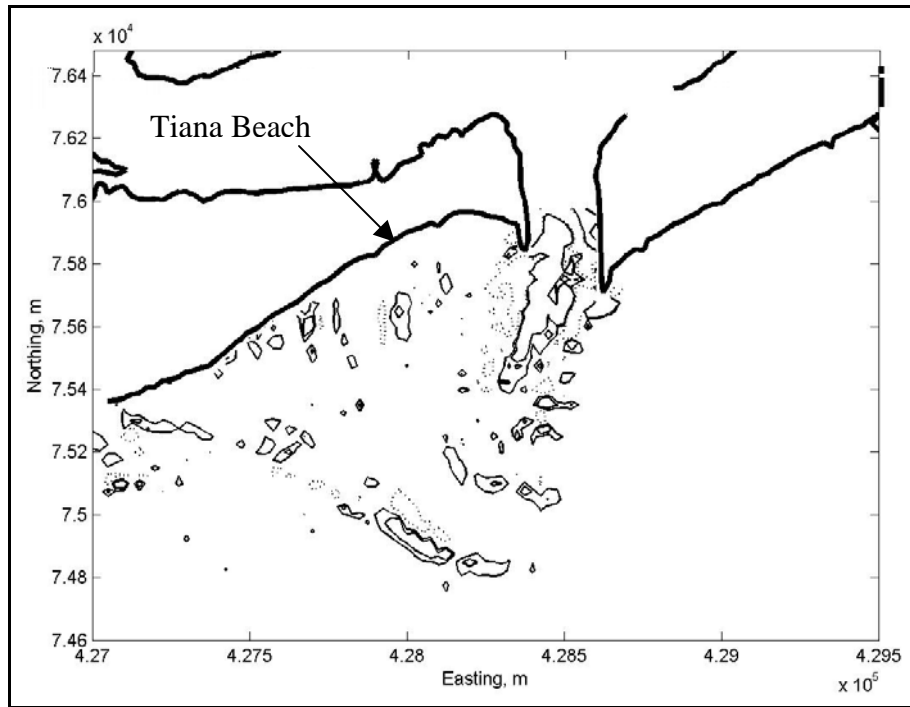


Figure 11. Calculated morphology change at end of September 1997. Contours were constructed at the 0.05 and 0.1 m intervals. Solid contours indicate zones of deposition and dotted lines indicate regions of erosion.

Wave activity began to increase during the month of October from both the southwest and southeast quadrants. Four significant events occurred in which wave heights exceeded 2 and 3 m, and periods ranged from 9 to 12 sec. Two of the events were from the southwest and resulted in longshore transport reversals. Active regions of morphology change were located along the coast of the east and west barrier, and in the inlet throat and channel (Fig. 11). Sediment was deposited along the bypass bar, attachment point and at the seaward extent of the ebb jet. Patterns of morphology change were similar to those calculated for August and September, but with larger erosion and accretion signals.

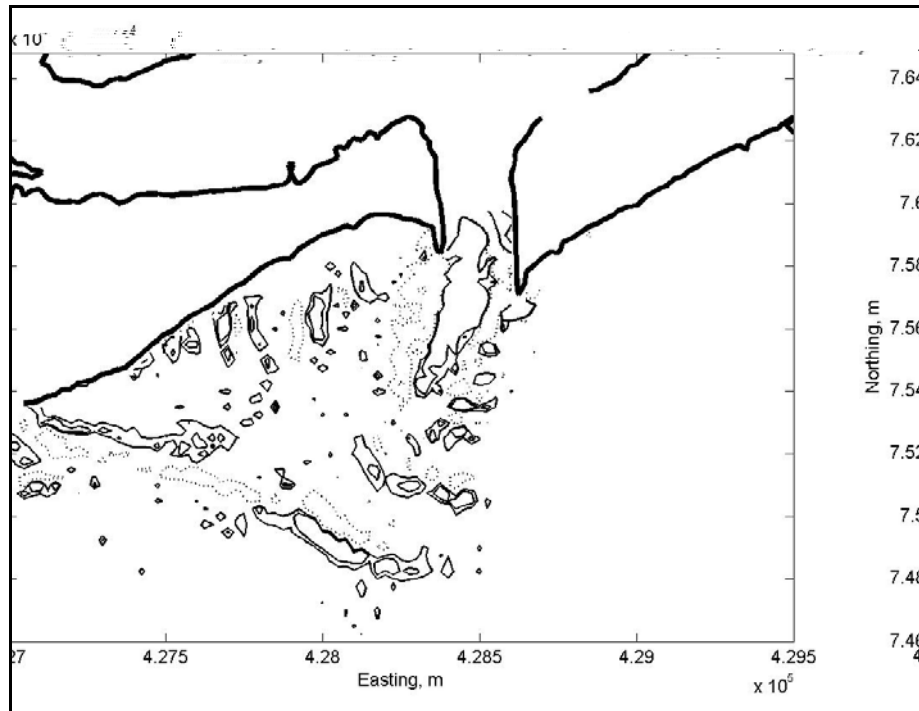


Figure 12. Calculated morphology change at end of October, 1997. See Fig.11 for description.

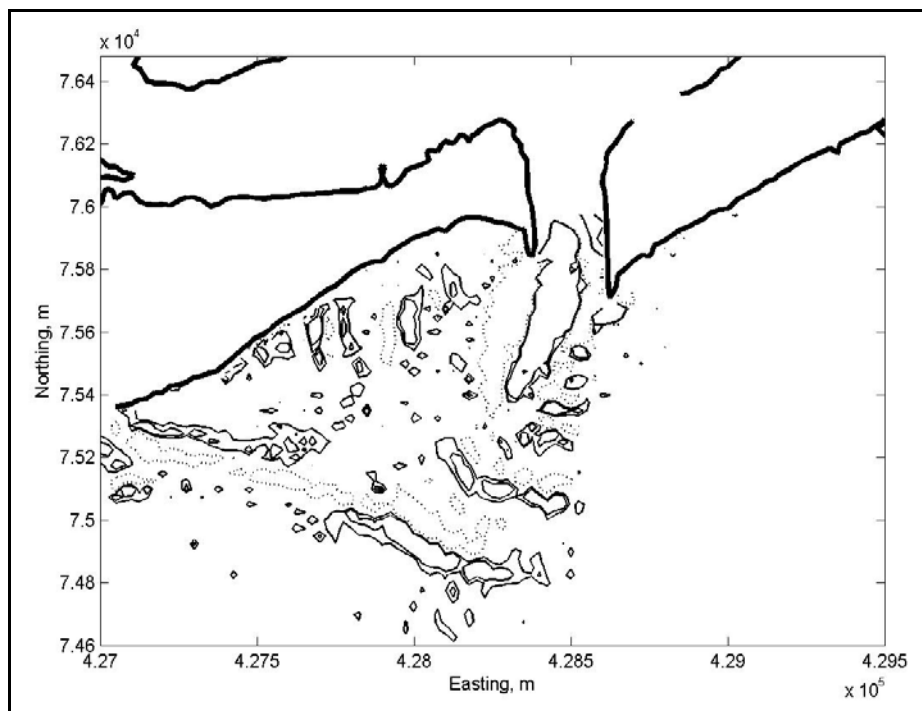


Figure 13. Calculated morphology change at end of November, 1997. See Fig.11 for description.

Shinnecock Inlet experienced five intense wave events during the month of November. For three of these events, wave heights exceeded 4 m and periods ranged between 10 and 11 sec from the southeast quadrant. The two smaller events (wave height of 2.5 to 3 m; period 7 to 9 sec) approached the inlet from the southwest. Bathymetry changes at the end of November indicated increased deposition along the bypass bar and seaward extent of the ebb jet, and continued westward deflection of the main channel (Fig. 12).

Discussion

Wave conditions for the simulation varied from low energy in the months of August and September to moderate and eventually high-energy environments for October, 1997 and November, 1997 respectively. Morphologic changes computed for the end of September indicated the regional influence of tidal transport was localized around the throat and mouth of the inlet and the pathway of the ebb jet. Westward migration of the channel thalweg was shown to occur during weak wave forcing. Two tidal processes are responsible for this migration. The periodic formation of the ebb jet scours the channel thalweg. In addition, the coastal tidal current advects the jet toward the west, which translates the erosional stresses of the jet westward. Together, these processes scour the western portion of the channel, which realigns of the thalweg.

Scouring of the navigation channel in the throat of the inlet throughout the simulation is consistent with the analytical relationship of Jarrett, 1976 (Eq. 1), and previous observations of the inlet (Militello and Kraus 2001b). Additionally the ebb shoal continued to evolve toward the equilibrium volume (Eq. 2) by accreting $14,370 \text{ m}^3$ of sediment over the fifteen-week period. Calculated modes of natural sediment bypassing were also in agreement with the theoretical stability ratio of Bruun and Geritsen (1959). Observed transport pathways were associated with channel flushing through the throat of the inlet and wave-driven transport along the perimeter of the ebb shoal and bypass bar.

Previous investigations have attributed the westward deflection of the main channel of Shinnecock Inlet attributes to: 1) continuous tidal deflection of the ebb jet (Militello and Kraus 2001a), and 2) increased deflection of the ebb jet by wave-driven longshore currents (Buonaiuto, 2003a). Other controls on the jet migration are the bay channel geometry, flood shoal, and offset jetties. Simulations conducted in this study indicate the continuous tidal deflection of the ebb jet is a dominant process controlling the migration of the channel, and it can be enhanced or accelerated by increased wave activity and littoral sediment supply. Further analysis is required to discern to what degree the observed changes in the morphology of Shinnecock Inlet between the 1997 and 1998 surveys were in response to an increase in sediment delivery. Sediment supplied to the inlet was most likely derived from wave driven erosion and transport of the beaches and surfzone along the eastern and western barriers.

Wind forcing was not included in the simulation, so wind-driven setup and setdown in the bay and near the coast were not represented. Although this forcing of water level would potentially alter tidal flushing through the inlet, breaking of waves and transport pathways of sediment on the ebb-shoal, its control on the hydrodynamics and sediment dynamics is expected to be secondary to waves and tides.

Additionally the sediment transport module was designed for a uniform grain size. In general the ebb and flood shoals, bypass bar and beaches are comprised of fine to medium sand (0.20 – 0.35 mm) and an assumed uniform grain size would produce reasonable results. However, the main navigation channel through the throat of the inlet could contain more coarse material including gravel and shell hash. This material would be more resistant to erosion and would not have scoured as rapidly as predicted by the present transport model.

There are certain weaknesses inherent in the condensed forcing approach of the modeling system, as well as limitations associated with the sediment transport module. Calculations of morphology and water levels are expected to improve by modeling the complete time period between surveys (8/13/97 through 5/28/98), and including time-varying wind stress in the momentum equations. Implementation of non-uniform grain sizes in the IMS is a planned enhancement, and once available simulations at Shinnecock Inlet will be conducted to take advantage of this capability.

Conclusions

Evolution of morphology at Shinnecock Inlet between August 13, 1997 and May 28, 1998 was found to be associated with the westward migration of the main channel. A coupled circulation, wave, and sediment transport modeling system was applied to calculate morphology change and to determine the primary controls on channel migration. General trends of natural sediment bypassing, growth of the ebb shoal, scour in the throat, and channel migration were reproduced by the IMS-M2D version forced by accurate tides and waves.

In summary, major measured morphologic change observed in at the inlet and ebb shoal was simulated successfully in the IMS. These changes were associated with the westward deflection of the channel seaward of the inlet, which include erosion of the western flank along the channel, shallowing of the eastern flank of the ebb shoal, and deposition along the seaward edge of the ebb shoal where the ebb jet terminates.

Channel deflection is controlled primarily by tidal processes consisting of periodic ebb jet formation and advection of the jet by the coastal tidal current. Waves originating from southeast enhance channel migration.

Acknowledgements

This research was sponsored by the Inlet Modeling System Work Unit of the Coastal Inlets Research Program, Coastal and Hydraulics Laboratory, U.S. Army

Engineer Research and Development Center. Permission was granted by Headquarters, U.S. Army Corps of Engineers, to publish this information.

References

- Bove, M. C., Elsner, J. B., Landsea, C. W., Niu, X., O'Brien, J. J (1998). Effect of El Nino on U.S. landfalling hurricanes, *Bulletin of the American Meteorological Society*, v.79, 2477-2482.
- Bruun, P., Gerritsen, F. (1959). Natural by-passing of sand at coastal inlets: *Journal of the Waterways and Harbors Division*, December, 75-107.
- Bruun, P., Gerritsen, F. (1960). Stability of coastal inlets, Amsterdam, North Holland Publishing Co., (Elsevier), 123 p.
- Buonaiuto, F.S. (2003a). Morphological evolution of Shinnecock Inlet, NY. Ph.d. dissertation, State University of New York at Stony Brook, Stony Brook, NY.
- Buonaiuto, F.S. (2003b). Principal component analysis and morphology change at Shinnecock Inlet, NY, *Proceedings Coastal Sediments '03*.
- Carr de Betts, E.E (1999). An examination of flood deltas at Florida's tidal inlets, University of Florida, Gainesville, FL thesis, Report No.UFL/COEL-99/015.
- Dean, R.G., Walton T.L. (1975). Sediment transport processes in the vicinity of inlets with special reference to sand trapping, *Estuarine Research*, Vol. 2, L.E. Cronin ed., Academic Press, New York, 129-149.
- Jarrett, J.T. (1976). Tidal prism – inlet area relationships, GITI Report No. 3, Coastal Engineering Research Center, U.S. Army Corps of Engineers, Fort Belvoir, Virginia, 32 p.
- Kana, T.W. (1995). A mesoscale sediment budget for Long Island, New York. *Marine Geology*. v.126, 87-110.
- Kraus, N.C. (2001). On equilibrium properties in predictive modeling of coastal morphology change, *Proceedings Coastal Dynamics '01*, ASCE, 1-15.
- LeConte, L.J. (1905). Discussions of notes on the improvement of rivers and harbor outlets in the United States, *Transactions of American Society of Civil Engineers*, 55, 306-308.
- Liu, J.T., and Hou, L. (1997). Sediment trapping and bypassing characteristics of a stable tidal inlet at Kaohsiung Harbor, Taiwan, *Marine Geology*, v.140, 367-390.
- Militello, A., Kraus, N.C. (2001a). Shinnecock Inlet, New York, Site Investigation Report 4: Evaluation of Flood and Ebb Shoal Sediment source Alternatives for the West of Shinnecock Interim Project, New York, Coastal and Hydraulics Laboratory, Technical Report CHL-98-32.
- Militello, A., and Kraus, N. C. (2001b). Re-Alignment of an Inlet Entrance Channel by Ebb-Tidal Eddies. *Proceedings Coastal Dynamics '01*, ASCE Press, New York, 423-432.

- Militello, A., and Kraus, N. C. (2004). Regional Circulation Model for Coast of Long Island, New York. *Eighth International Estuarine and Coastal Modeling Conference 2003*. (This volume.)
- Militello, A., Reed, C. W., and Zundel, A. K. (2004). *Two-Dimensional Circulation Model M2D: Version 2.0, Report 1, Technical Documentation and User's Guide*. Coastal Inlets Research Program Contractor's Report ERDC-CHL-CR-__-__, U.S. Army Engineer Research and Development Center, Vicksburg, MS (in press).
- Morang, A. (1999). Shinnecock Inlet, New York, Site Investigation, Report 1, Morphology and Historical Behavior. Coastal Inlets Research Program, USACE Waterways Experiment Station, Coastal and Hydraulics Laboratory. TR-CHL-98-32.
- O'Brien, M.P. (1931). Estuary tidal prisms related to entrance areas, *Civil Engineering*, v. 1, n. 8, 738-739.
- O'Brien, M.P. (1969). Equilibrium flow areas of tidal inlets on sandy coasts, *Journal of the Waterways and Harbors Division*, ASCE, v. 95, n. WW1, 43-52.
- Panuzio, F. L. (1968). The Atlantic Coast of Long Island, *Proceedings 11th Coastal Engineering Conference*, ASCE, 1,222-1,241.
- Research Planning Institute (1983). Sediment Budget analysis, Fire Island Inlet to Montauk Point, Long Island, New York – reformulation study, Report prepared for U.S. Army Engineer District, New York, Research Planning Institute, Inc. , Columbia, SC.
- Rosati, J.D., Gravens, M.B., Gray Smith, W. (1999). Regional sediment budget for Fire Island to Montauk Point, New York, USA, *Proceeding Coastal Sediments '99*, 802-817.
- Schwab, W.C., Thieler, E.R., Foster, D.S., Denny, J.F., Swift, B.A., Danforth, W.W., Allen, J.R., Lotto, L.L., Allison, M.A., Gayes, P.T., Donovan-Ealy, P. (1997). Mapping the inner shelf off southern Long Island, N.Y.; Implications for coastal evolution and behavior. *EOS Transactions*, American Geophysical Union. v. 78.
- Smith, J. M., Sherlock, A. R., Resio, D. T. (2000). STWAVE: Steady-State Spectral Wave Model User's Manual for STWAVE Version 3.0. USACE, ERDC/CHL SR-01-1.
- Taney, N.E. (1961). Geomorphology of the South Shore of Long Island, New York. Beach Erosion Board, T.M. n. 128.
- U.S. Army Corps of Engineers (1958). Moriches and Shinnecock Inlets, Long Island, New York, survey report, U.S. Army Engineer District, New York.
- U.S. Army Corps of Engineers (1988). General Design Memorandum Shinnecock Inlet Project, Long Island, New York, Reformulation Study and Environmental Impact Statement, U.S. Army Engineer District, New York.
- Walton Jr., T.L., Adams, W.D. (1976). Capacity of inlet outer bars to store sand, *Proceedings 15th Coastal Engineering Conference*, UACE, 1919-1937.
- Watanabe, A. 1987. 3-dimensional Numerical Model of Beach Evolution. *Proceedings Coastal Sediments '87*, ASCE, 802-817.

- Williams, S.J. (1976). Geomorphology, shallow bottom structure and sediments of the Atlantic inner continental shelf off Long Island. NY Tech Paper, 76-2. USACE, Ft. Belvoir, Virginia, 123 p.
- Williams, G.L., Morang, A., Lillycrop, L. (1998). Shinnecock Inlet, New York, Site Investigation, Report 2: Evaluation of Sand Bypass Options, US Army Corps of Engineers, Waterways Experiment Station, Technical Report CHL-98-32.
- Zundel, A.K. (2000). Surface-water modeling system reference manual, Brigham Young University, Environmental Modeling Research Laboratory, Provo, UT.